

# Using Booster, Switchyard and MI-8 in Project X

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# Overview

- Goal is to use as much as the existing infrastructure as possible for Project X
  - Use switchyard tunnel for linac.
  - Use existing Booster tunnel
  - Use upgraded Booster RF.
    - Upgrades to Booster to take into account Project X requirements.
  - Injection to MI is using present MI-8 line.

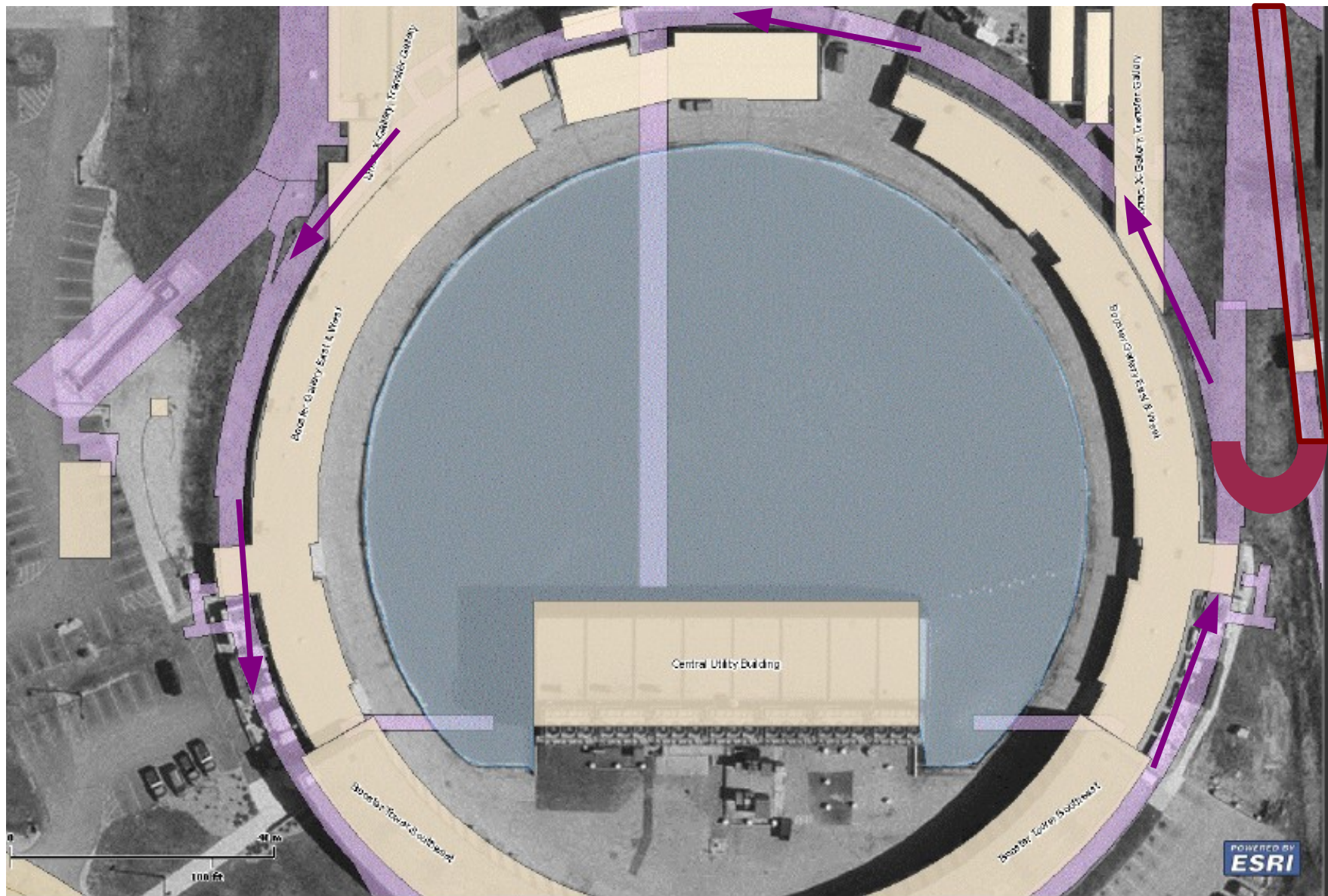
# Aerial Shot





Approximate  
position of  
linac and  
bend

# Siting 1 to 1.5 GeV linac in Switchyard Transfer Line



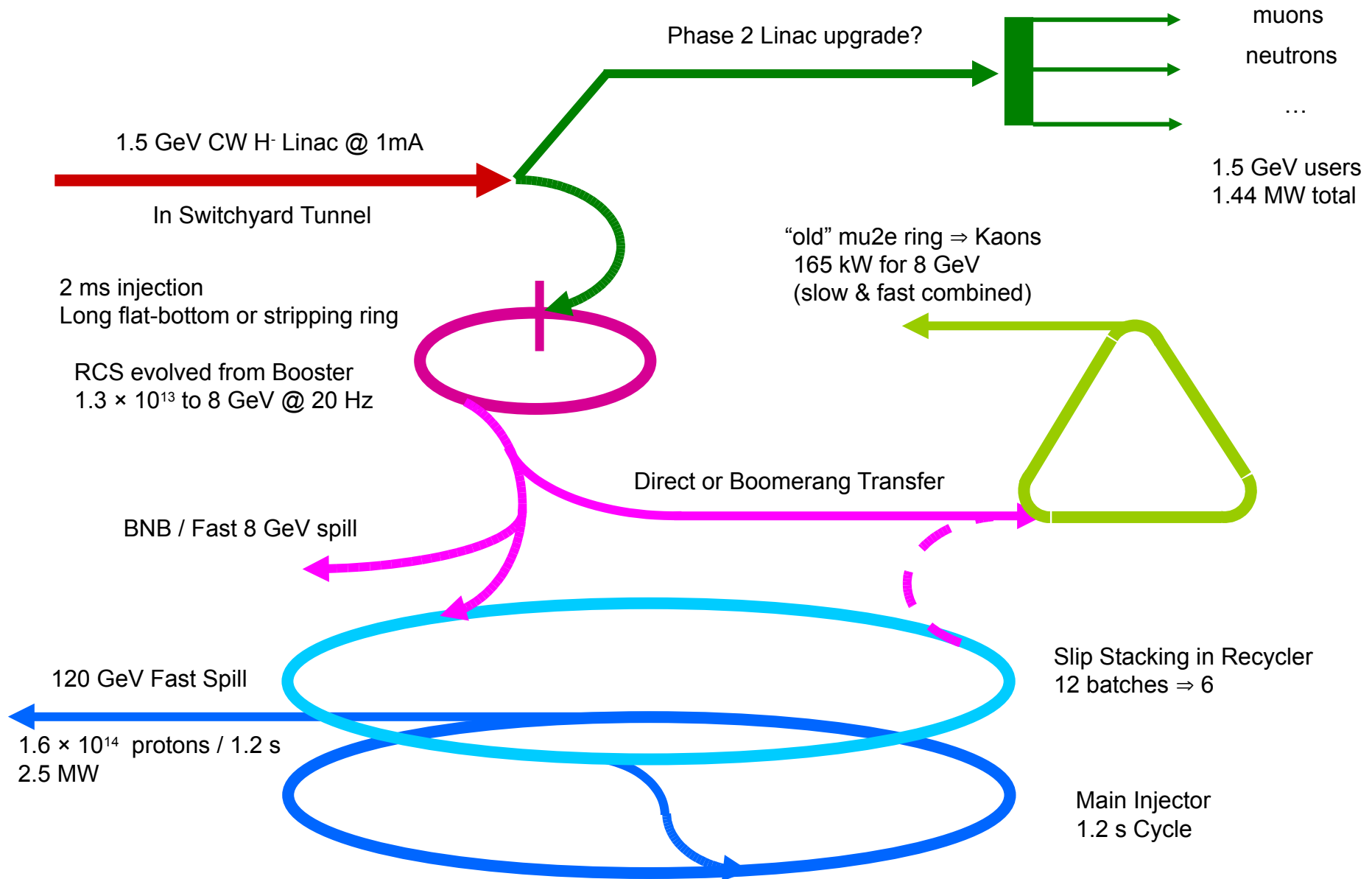
~100m  
for  
1GeV  
linac

Min  
radius of  
14m for  
1% loss  
of H-  
from  
stripping

# The Injector Chain

- H- source
- RFQ
- Linac 1.5GeV fits in present enclosures
  - Pulsed or CW operation (can feed muon expt)
- Booster/RCS
  - Using present MI-8 line to inject into MI/RR.
- Slow spill
  - Inject into Tev tunnel from MI using P1 line for slow spill.
  - Or spill from mu2e.
- Slip stacking in RR
  - Accept 12 Booster batches.
- MI 2MW beam for neutrino experiments.

# PrX IC- $\alpha$



# Pulsed

- 20Hz linac (1.2 ms pulse length)
  - Same frontend as ICD1 except injection is at 1.5GeV
- Current is 20mA
  - $\leq 200$  us to fill Booster
  - Remainder of 1.2ms pulse goes to 1.5GeV experiments

# CW

- 1mA CW linac
- Injection into Booster/RCS for  $\leq 4\text{ms}$  at 20Hz.
- Same frontend as ICD2
  - Rest of duty factor goes to 1.5GeV experiments.

# RCS

- Reuse present tunnel
- Redesign lattice
  - Increase transition energy  $> 8\text{GeV}$
- Injection energy is 1 GeV to 1.5GeV
- Ramp rate is 20 Hz
- Extra cycles (MI is at 10Hz for 1.2 s cycle time, 1 s cycle time should be considered)
  - For 8 GeV experiments
- $1.04 \times 10^{13}$  protons per batch (this is not a limit) for 2MW MI beam

# Increase in Beam Current

- By injecting at a higher energy, we can increase the beam current in the new Booster.
- Using the present maximum space charge tune shift at injection (400MeV) as starting point, we get the following increase injection beam intensity
  - Injection at 1GeV gives 2.5x increase
  - Injection at 1.5GeV gives 4.3x increase
- Efficiency must be increased
  - Reduced injection losses from chopping and higher energy
  - Larger aperture through RF
  - No notching losses – performed with chopper
  - No crossing transition

# Pros/Cons compared to ICD1/2

- Less digging
- Use existing infrastructure like cryo CHL is right there, power, water etc.
- Booster components like correctors, septas, RF solid state drivers.
- MI test beam, switchyard is removed.
- Some decommissioning of Booster components.

# Phase Relationships

	NOvA/LBNE	mu2e	Kaons	Other @ 1.5-3 GeV	Other @ 8 GeV
Phase 0	700 kW	0-30 kW	0	0	0-10 kW
IC-2v2 Phase 1	700 kW	400 kW	800 kW	800 kW	0-40 kW
IC-2v2 Phase 2	2.3 MW	400 kW	800 kW	800 kW	Large ?
IC- $\alpha$ Phase 1	2.5 MW	200 kW	150 kW	1.2 MW	15+ kW
IC- $\alpha$ Phase 2	2.5 MW	600 kW	1.2 MW	1.2 MW	165 kW

- Beam is extremely limited in Phase 0
  - Booster only has about enough capability for 700 kW NOvA/LBNE (w/o upgrades)
  - Every 10 kW for mu2e costs 150kW of neutrino

Assume IC- $\alpha$  Phase 2 is 3 GeV linac (ala IC-2v1) - for comparison

- My take (Zwaska):
  - muons and Kaon experiments need to be phased
    - Mu2e claim: they need to run the lower intensity experiment to learn how to build the second experiment
    - Kaons may be in a similar case.
  - Neutrino experiments have coveted 2 MW since MINOS and the Proton Driver

Extra Slides

# Max B-field for 1 GeV H- Ions

From J.P. Carneiro's paper (fnal\_2740.pdf), the H- ion lifetime in its rest frame is given by 2 params, a and b.  
For 1 GeV H- ions, I will use the 800MeV data.

a and b here are the average of the two numbers in Table 1

```
In[1]:= a = (2.47 + 3.073) / 2 10^-14; (*S MV/cm *)
b = (44.94 + 44.14) / 2; (* MV/cm *)
```

Note : J.P.'s equation was  $a/e \exp[b/e]$ . Clearly  $c > b$ . See "Handbook of Accelerator Physics and Engineering", pg 442.

```
In[3]:= tau0[e_] := a / e Exp[b / e]
```

The fraction lost per meter is given by

```
In[4]:= lambda[e_] := 1 / (c beta gamma tau0[e])
```

For 1 GeV H- ions,  $\beta \gamma$  can be calculated as follows:

```
In[5]:= m0 = 938; (*MeV/c^2 *)
ke = 1000; (*MeV *)
```

```
In[7]:= etot = m0 + ke;
```

```
In[8]:= gamma = etot / m0 // N
```

```
Out[8]= 2.0661
```

```
In[9]:= Solve[gamma == 1 / (sqrt[1 - beta^2], beta]
```

```
Out[9]= {{beta -> -0.875066}, {beta -> 0.875066}}
```

```
In[10]:= beta = beta /. %9[[2, 1]]
```

```
Out[10]= 0.875066
```

```
In[11]:= c = 3 * 10^8; (*m/s *)
```

The momentum p of the H- ion at 1GeV is

```
In[12]:= p = Sqrt[etot^2 - m0^2] 10^-3 // N; (*GeV/c *)
```

```
In[13]:= p
```

```
Out[13]= 1.69588
```

A 1 GeV H- sees the following e-field for a B-field [T]

```
In[14]:= Ef[B_] := 3.197 p B
```

## The Solution

I want to calculate the maximum B-field allowed for 1% loss of H-. It depends on the length of the curve! From Bill, the angle required is 180 degrees. This means that the distance covered by the 1GeV H- given the radius of curvature is

```
In[15]:= d[r_] := pi r
```

r is given by the relationship between magnetic rigidity and momentum:

$B r = 3.3357 p$ , with B in teslas, r in metres, p in GeV/c. Therefore

```
In[16]:= r[Bf_] := 3.3357 / Bf p
```

The loss of H- must be  $\leq 1\%$  for the entire distance the H- travels in a magnetic field, i.e

$d[r] \lambda[e] \leq 0.01$

or

$d[r[Bf]] \lambda[Ef[Bf]] \leq 0.01$

Let's find the maximum B-field allowed

```
In[17]:= FindRoot[d[r[Bf]] lambda[Ef[Bf]] == 0.01, {Bf, 0.1}]
```

```
Out[17]= {Bf -> 0.405114}
```

i.e. Maximum Bfield is 0.4 T. This translates to a minimum radius of curvature of

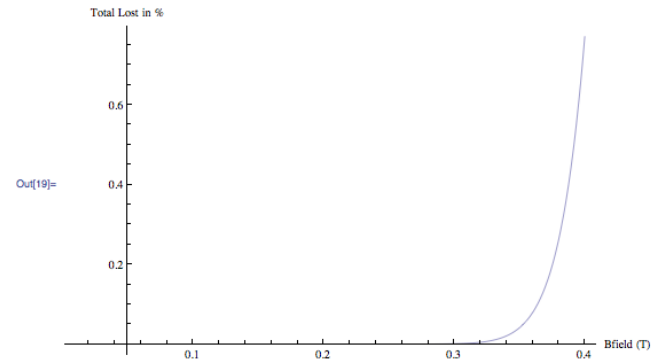
```
In[18]:= r[Bf] /. %17[[1]]
```

```
Out[18]= 13.9638
```

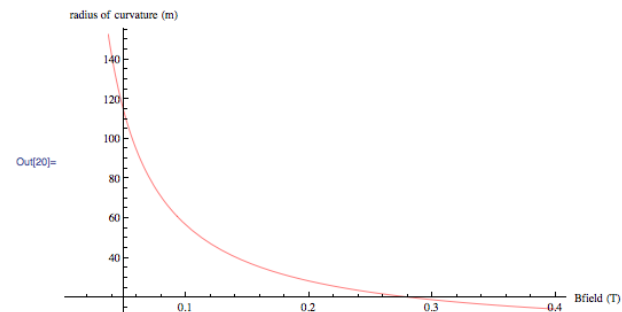
i.e. 14 m

## Plots

```
In[19]:= Plot[lambda[Ef[Bf]] d[r[Bf]] 100, {Bf, 0.01, 0.4},
  AxesLabel -> {"Bfield (T)", "Total Lost in %"}, PlotRange -> All]
```

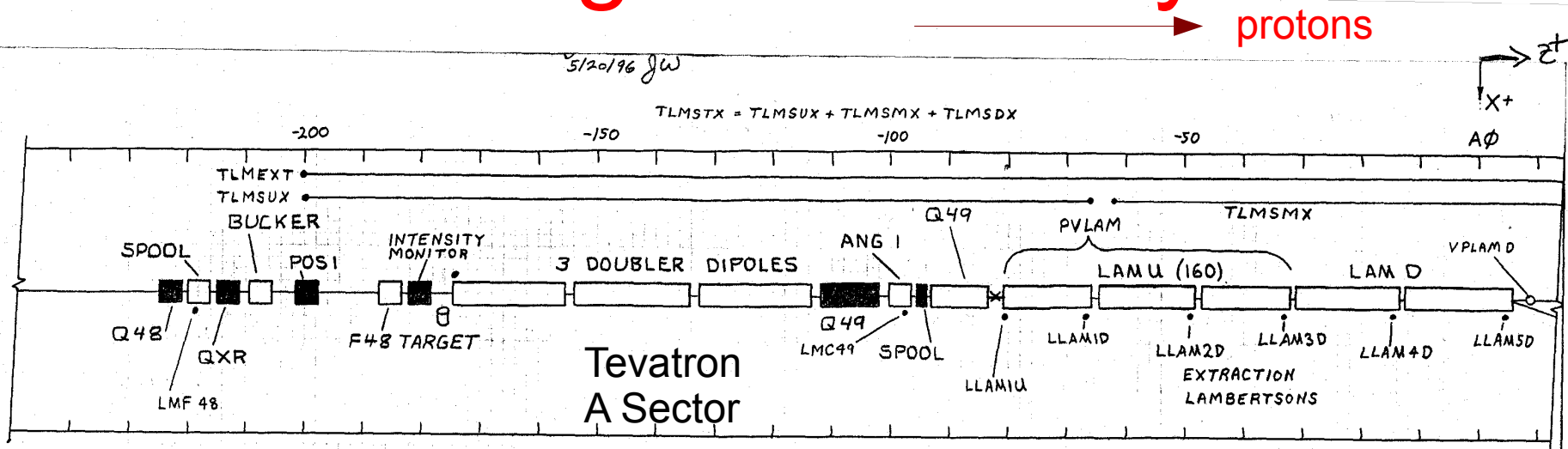


```
In[20]:= Plot[r[Bf], {Bf, 0.01, 0.4}, PlotStyle -> RGBColor[1, 0, 0],
  AxesLabel -> {"Bfield (T)", "radius of curvature (m)"}]
```



Minimum bending radius for 1% loss of H- is 14m from magnetic stripping.

# Total Length of Switchyard line

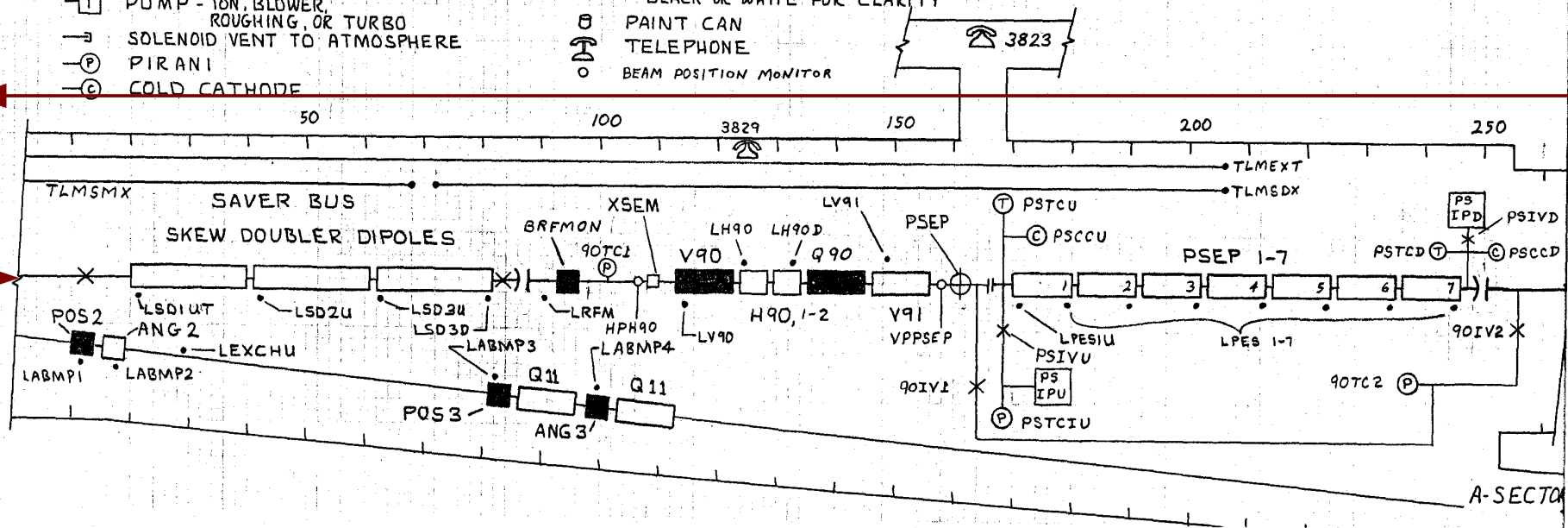


## SYMBOLS

- |— WINDOW
- X— VALVE
- ⊕— SWIC
- T— PUMP - ION, BLOWER, ROUGHING, OR TURBO
- >— SOLENOID VENT TO ATMOSPHERE
- P— PIRANI
- C— COLD CATHODE

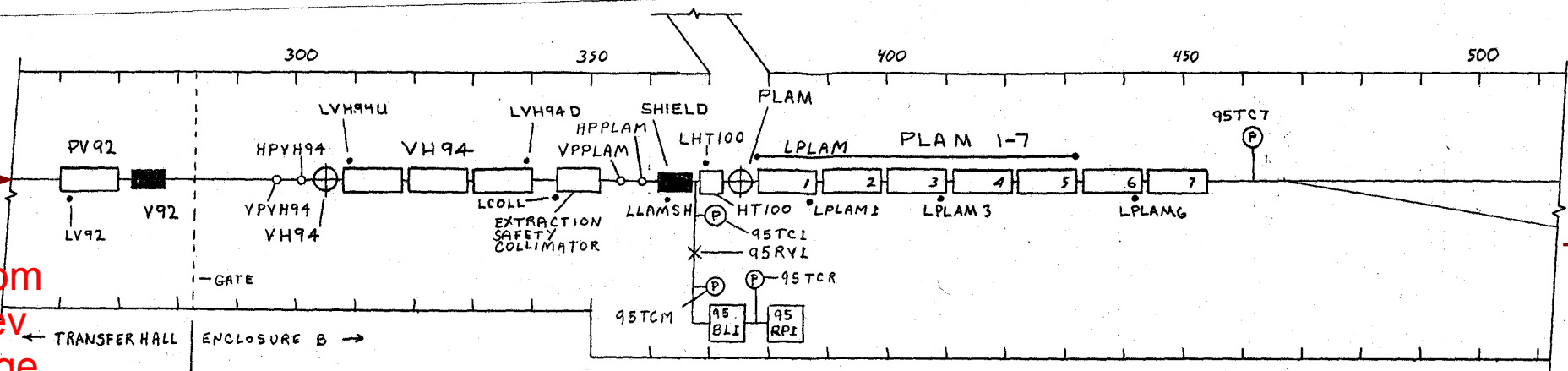
- LOSS MONITOR
- LONG LOSS MONITOR
- BEAMLINE ELEMENT, ARBITRARILY BLACK OR WHITE FOR CLARITY
- ⊗ PAINT CAN
- ☎ TELEPHONE
- BEAM POSITION MONITOR

## TRANSFER HALL

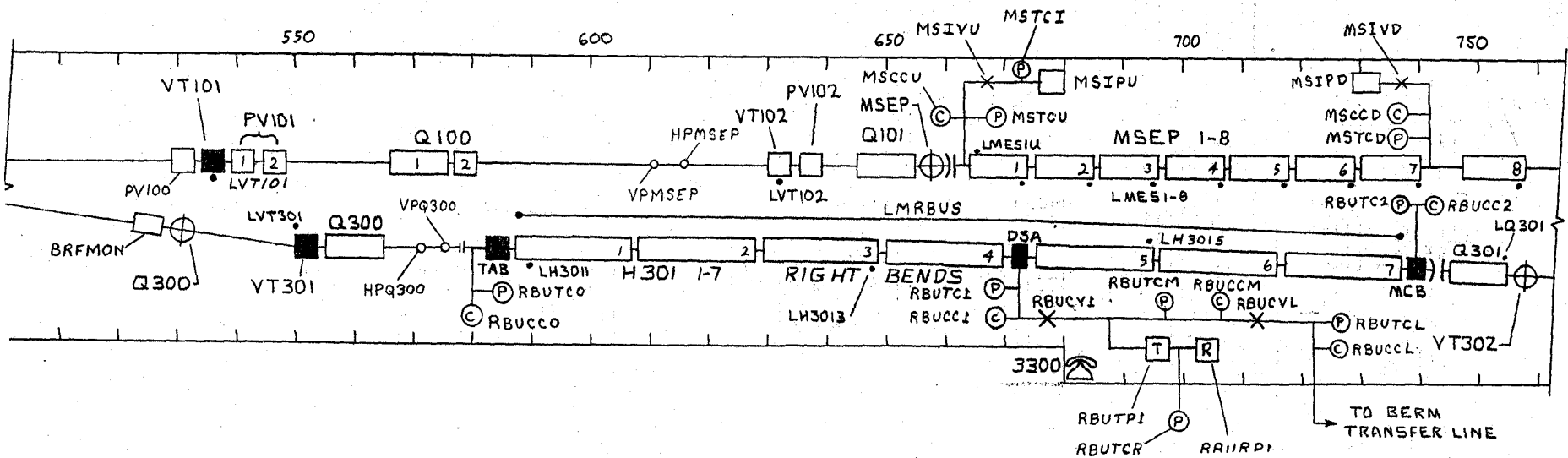


Next page

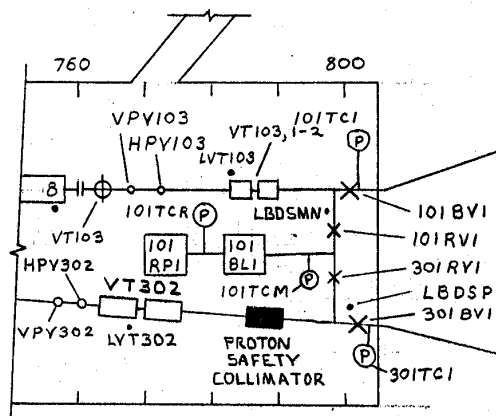
From  
prev  
page



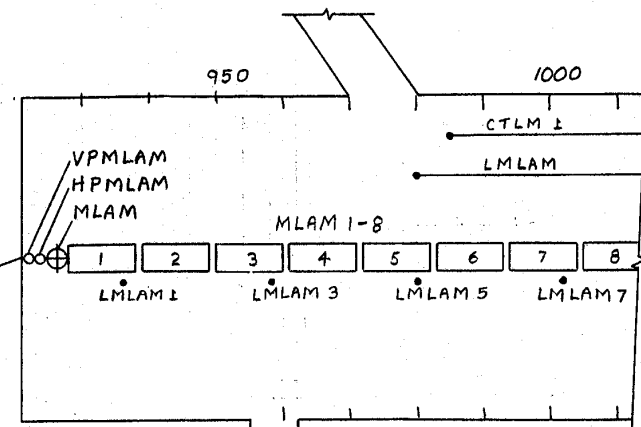
## ENCLOSURE B



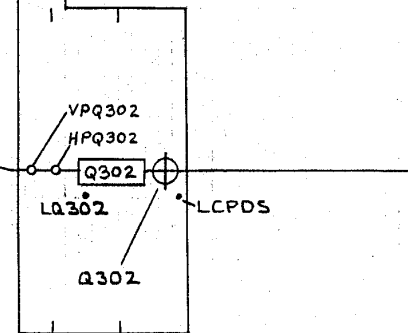
J. Walton  
5/24/96  
JW



ENCLOSURE B



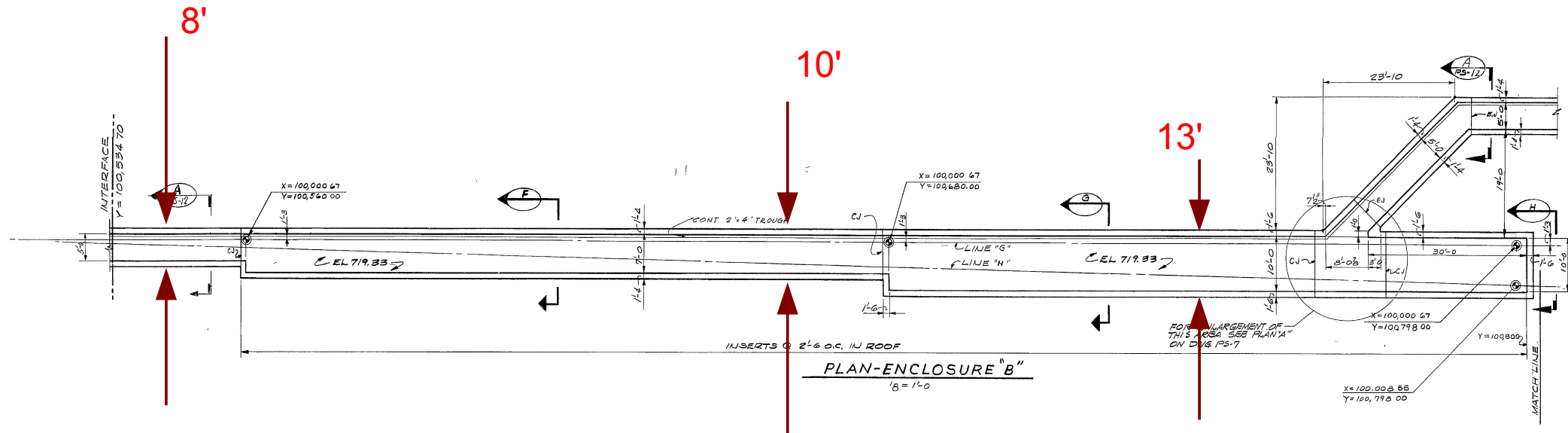
ENCLOSURE C



G-NOTCH

Total available length for 1 to  
1.5 GeV linac is about 1000 ft  
~ 300m

# Enclosure B Plan View



# FODO Lattice for new Booster

- A new FODO lattice with a transition energy of **10GeV (> 8GeV)** and preserves the **fractional tune of 0.7** for Booster can have the following parameters
  - Transition energy: 10GeV
  - Betatron Tune: 12.7
  - FODO length: 11.14m
  - Phase advance per cell: 109 deg.
  - Bend angle per cell: 8.6 deg
  - Total number of cells: 42

# FODO Lattice for Upgraded Booster

The FODO cell is defined as  $\left[ \frac{1}{2} QF B Q D B \frac{1}{2} QF \right]$ , B is a bend dipole of length L and bending angle  $\theta$ .

Using SY Lee's equations after (2.267)

$$\alpha t = \frac{(Df + Dd) \theta}{2 L} = \frac{\theta^2}{\sin[\phi/2]^2},$$

where Df and Dd are defined by exercise 2.4.2,  $\phi$  is the phase advance of one FODO cell.

## Selecting the number of FODO cells

I am going to fix the number of 1/2 cells to be 84 (or number of FODO cells is 42).

In[1]:= **n = 84;**

Then the bend angle per half cell is

In[2]:=  **$\theta = 2 \pi / n // N$**

Out[2]= 0.0747998

And the length per half cell is

In[3]:= **R0 = 74.47; (\*m, Radius of Booster\*)**

In[4]:= **L = 2  $\pi$  R0 / n**

Out[4]= 5.57034

i.e. the length of each FODO cell is thus  $2*L = 11.14$  m.

If I keep the fractional part of the betatron tune to be 0.7 (like in the present Booster), I am going to choose the total phase advance per revolution to be

In[5]:=  **$\phi_{tot} = 12.7 \times 2 \pi$**

Out[5]= 79.7965

Which means that the phase advance per FODO cell is

In[6]:=  **$\phi = \phi_{tot} / (n / 2)$**

Out[6]= 1.89992

or in degrees is

In[7]:=  **$\phi \text{ 180} / \pi // N$**

Out[7]= 108.857

The n/2 is because if n is the number of half cells and so the number of FODO cells is n/2.

I can calculate  $\alpha t$  by using

$$\alpha t = \theta^2 / \sin[\phi / 2]^2$$

In[8]:=  **$\alpha t = \theta^2 / \sin[\phi / 2]^2 // N$**

Out[8]= 0.00845673

And so  $\gamma t = 1/\text{Sqrt}[\alpha t]$

In[9]:=  **$\gamma t = 1 / \text{Sqrt}[\alpha t]$**

Out[9]= 10.8742

The transition energy is thus

In[10]:=  **$m0 = 938 \times 10^6; (*eV/c^2*)$**

In[11]:=  **$\gamma t m0 // N$**

Out[11]=  $1.02 \times 10^{10}$

which is 10 GeV and is LARGER than 8 GeV.

# Space Charge Tune Shift

Only the coherent space charge tune shift is relevant for limiting the number of protons in the new Booster.

The scaling of this effect is from (4.86, page 151) of Ng which is  $N / \beta \gamma^2$ . If I believe that the maximum space charge tune shift of Booster is 0.4 (Table 4.2, page 157 of Ng) for injection at 400MeV, I can see how much more protons I can inject at 1GeV and 1.5 GeV.

First, I have to calculate  $\beta$  and  $\gamma$  at 400 MeV , 1 GeV and 1.5 GeV

```
In[1]:= m0 = 938 * 10^6; (*eV*)

In[2]:= k400 = 400 * 10^6; (*eV*)
k1000 = 1 * 10^9; (*eV*)
k1500 = 1.5 * 10^9; (*eV*)
```

## Calculate the $\gamma$ and $\beta$ for each energy

```
■ 400 MeV

In[6]:= Solve[γ m0 == m0 + k400, γ] // N
Out[6]:= {{γ -> 1.42644}}

In[7]:= γ400 = γ /. First[%]
Out[7]:= 1.42644

In[8]:= Solve[1/Sqrt[1 - β^2] == γ400, β]
Out[8]:= {{β -> -0.713116}, {β -> 0.713116}}

In[9]:= β400 = β /. Last[%]
Out[9]:= 0.713116
```

```
■ 1000 MeV

In[10]:= Solve[γ m0 == m0 + k1000, γ] // N
Out[10]:= {{γ -> 2.0661}}

In[11]:= γ1000 = γ /. First[%]
Out[11]:= 2.0661

In[12]:= Solve[1/Sqrt[1 - β^2] == γ1000, β]
Out[12]:= {{β -> -0.875066}, {β -> 0.875066}}

In[13]:= β1000 = β /. Last[%]
Out[13]:= 0.875066
```

```
■ 1500 MeV

In[14]:= Solve[γ m0 == m0 + k1500, γ] // N
Out[14]:= {{γ -> 2.59915}}

In[15]:= γ1500 = γ /. First[%]
Out[15]:= 2.59915

In[16]:= Solve[1/Sqrt[1 - β^2] == γ1500, β]
Out[16]:= {{β -> -0.923024}, {β -> 0.923024}}

In[17]:= β1500 = β /. Last[%]
Out[17]:= 0.923024
```

## Scaling

The scaling is  $\Delta \nu \propto N / \beta \gamma^2$  and so

$$\frac{\Delta \nu}{\Delta \nu_{400}} = \frac{N_e}{N_{400}} \frac{\beta_{400} \gamma_{400}^2}{\beta_e \gamma_e^2} = f \frac{\beta_{400} \gamma_{400}^2}{\beta_e \gamma_e^2}$$

where  $f$  is the factor which describes the increase in beam current when  $\Delta \nu / \Delta \nu_{400} = 1$ . Therefore,

$$f = \frac{\beta_e \gamma_e^2}{\beta_{400} \gamma_{400}^2}$$

### ■ Increase in beam current for 1 GeV

```
In[18]:= f1000 = (β1000 γ1000^2) / (β400 γ400^2)
Out[18]:= 2.5744
```

### ■ Increase in beam current for 1.5 GeV

```
In[19]:= f1500 = (β1500 γ1500^2) / (β400 γ400^2)
Out[19]:= 4.29743
```

# Heating by Eddy Current

- Formula for power loss per unit length (W/m) is
  - $\frac{dP}{ds} = \pi^3 f_{\text{ramp}}^2 (B_{\text{max}} - B_{\text{min}})^2 r^3 d / \rho$ 
    - Formula is from Chao and Tigner “Handbook of Accelerator Physics and Engineering”, page 436.
  - For stainless steel pipe of thickness  $d=0.7\text{mm}$  and radius  $r=2\text{ cm}$ ,  $\rho=1/(1.4 \times 10^6) \Omega\text{m}$ ,  $f_{\text{ramp}} = 15\text{Hz}$
- For 1 GeV injection, 8GeV extraction, loss is 6W/m.
- For 1.5GeV injection, 8GeV extraction, loss is 5W/m

# Power Dissipated From Eddy Currents

The formula for time averaged power for a circular pipe of radius  $r$  comes from Chao and Tigner "Handbook of Accelerator Physics and Engineering", page 436.

$$P/L [W/m] = \pi^2 f^2 B_0^2 r^3 d / \rho$$

where  $f$  is frequency in Hz,  $B_0$  = maximum B field in Teslas,  $r$  is the radius of the beam pipe in metres,  $d$  is the thickness of the beam pipe,  $\rho$  the resistivity of steel in  $\Omega$  m. This formula is for half sine wave ramp.

Note that this formula is for ramping from 0 field to max B field, we are NOT doing this. We are ramping from injection B field to max B field. This should be equivalent to ramping from 0 to (Bmax-Binj). So my calculation will reflect this.

```
In[1]:=  $\rho = 1 / (1.4 \times 10^6);$  (* $\Omega$  m from Chao "Physics of Collective Instabilities" page 43*)  
 $r = 2 \times 10^{-2};$  (*m*)  
 $d = 0.7 \times 10^{-3};$  (*m*)  
 $f_{ramp} = 15;$  (*Hz*)
```

## $\Delta B$

To calculate  $\Delta B$ , I need to know the momentum of the protons at injection which is either 1GeV or 1.5GeV and extraction at 8GeV. Using the formula

$B r = 3.3357 p$  with  $B$  in Teslas,  $r$  in metres and  $p$  in GeV/c,  
I can calculate Bmin and Bmax.

The mass of a proton is

```
In[2]:=  $m_0 = 938 \times 10^6;$  (*eV/c2*)
```

The radius of the Booster is

```
In[8]:=  $R_0 = 74.47;$  (*m*)
```

### ■ Injection at 1 GeV

The momentum of 1 GeV proton is

```
In[3]:=  $k_1 = 1 \times 10^9;$  (*eV*)
```

```
In[5]:=  $p_1 = \text{Sqrt}[(m_0 + k_1)^2 - m_0^2] // N$ 
```

```
Out[5]=  $1.69588 \times 10^9$ 
```

In GeV/c

```
In[6]:=  $p_1 = p_1 10^{-9};$  (*GeV/c*)
```

The magnetic field strength is

```
In[9]:=  $B_1 = 3.3357 p_1 / R_0$ 
```

```
Out[9]=  $0.0759626$ 
```

### ■ Injection at 1.5 GeV

The momentum of 1.5 GeV proton is

```
In[10]:=  $k_{15} = 1.5 \times 10^9;$  (*eV*)
```

```
In[11]:=  $p_{15} = \text{Sqrt}[(m_0 + k_{15})^2 - m_0^2] // N$ 
```

```
Out[11]=  $2.25033 \times 10^9$ 
```

In GeV/c

### ■ Extraction at 8 GeV

The momentum of 8 GeV proton is

```
In[14]:=  $k_8 = 8 \times 10^9;$  (*eV*)
```

```
In[15]:=  $p_8 = \text{Sqrt}[(m_0 + k_8)^2 - m_0^2] // N$ 
```

```
Out[15]=  $8.88864 \times 10^9$ 
```

In GeV/c

```
In[16]:=  $p_8 = p_8 10^{-9};$  (*GeV/c*)
```

The magnetic field strength is

```
In[17]:=  $B_8 = 3.3357 p_8 / R_0$ 
```

```
Out[17]=  $0.398145$ 
```

## Eddy Current Heating

Power loss per unit length (W/m) for a circular beam pipe with half-sine wave ramp starting from injection B field to B extraction.

```
In[22]:=  $P[\Delta B\_ ] := \pi^2 f_{ramp}^2 \Delta B^2 r^3 d / \rho$ 
```

### ■ 1 GeV injection

```
In[23]:=  $P[B_8 - B_1]$ 
```

```
Out[23]=  $5.67743$ 
```

i.e. dissipation is about 6 W/m at 15Hz for a round stainless steel pipe.

### ■ 1.5 GeV injection

```
In[24]:=  $P[B_8 - B_{15}]$ 
```

```
Out[24]=  $4.83587$ 
```

i.e. dissipation is about 5 W/m at 15Hz for a round stainless steel pipe.

# RF Power

- Average RF power to beam at 1GeV injection energy: 440kW
- Average RF power to beam at 1.5GeV injection energy: 400kW

# RF Power

Number of protons for Project X

$$\text{In}[1]:= n = 2.6 \times 10^{13};$$

Energy ramps from 1 GeV to 8 GeV or 1.5 GeV to 8 GeV.  
For the 1 GeV case

$$\text{In}[2]:= \Delta E1 = 8 \times 10^9 - 1 \times 10^9; \text{ (*eV*)}$$

For the 1.5 GeV case

$$\text{In}[3]:= \Delta E15 = 8 \times 10^9 - 1.5 \times 10^9; \text{ (*eV*)}$$

Frequency of injection and ramp

$$\text{In}[4]:= \text{framp} = 15; \text{ (*Hz*)}$$

Charge of electron

$$\text{In}[5]:= q = 1.6 \times 10^{-19}; \text{ (*C*)}$$

---

## Average RF power to beam for 1 GeV injection

$$\text{In}[6]:= P1 = n \Delta E1 q \text{framp}$$

$$\text{Out}[6]= 436800.$$

or 440 kW

---

## Average RF power to beam for 1.5 GeV injection

$$\text{In}[7]:= P15 = n \Delta E15 q \text{framp}$$

$$\text{Out}[7]= 405600.$$

or 400 kW

---

## Peak Power

Peak RF power to beam occurs at 8 GeV and flattop time is ?? us